

# First Steps in Direct Imaging of Planetary Systems Like our Own: The Science Potential of 2-m Class Optical Space Telescopes

Karl Stapelfeldt<sup>1</sup>, John Trauger, Wesley Traub (NASA-JPL)  
Mark Clampin, William Oegerle, Jennifer Wiseman (NASA-GSFC)  
Olivier Guyon (Subaru Telescope)

## 1. The Exoplanet Science Landscape in 2015

A planetary system consists of gas giant planets, rocky terrestrial planets, and belts of small bodies which generate debris particles. Ongoing research and upcoming instrumental developments promise to significantly advance our knowledge of these three exoplanetary system components in the coming decade. Radial velocity surveys have already found a planet with half the mass of Neptune around an M star (Rivera et al. 2005). Around Sun-like stars, they will probe for Neptune-mass planets orbiting within 1 AU and Jupiter-mass planets orbiting as distant as 7 AU. For the very low mass stars, they may achieve detections of objects as small as a few Earth masses at orbital distances of a few tenths of an AU (Udry et al. 2007). The orbital element distribution for the inner jovian planets of nearby stars should be well in hand by 2015.

Upcoming transit observations will reveal the frequency and radii of close-in ( $a < 1$  AU) rocky exoplanets by photometrically monitoring large ensembles of solar-type stars. The COROT mission will find examples of large terrestrial planets with orbital periods  $< 2$  months by 2009, while Kepler will find Earth mass planets in 1 AU orbits by 2013. Near-infrared studies have the potential to do the same for M stars (where the small stellar size maximizes the transit depth). Numerous hot Jupiters will be found, including some by their integrated reflected light. Spectroscopic measurements made during transit and secondary eclipse by Spitzer, the upgraded HST, and JWST will constrain the albedos of these planets, and detect a few very high opacity atmospheric species such as Na I and Ly  $\alpha$  (Charbonneau et al. 2007). By 2015, transit work should have yielded a strong statistical understanding of the inner parts of extrasolar planetary systems.

High contrast imaging detections of brown dwarf companions to nearby stars are anticipated from large groundbased telescopes deploying the next generation of adaptive optics systems, and from space using JWST and perhaps Spitzer. Contrasts approaching  $10^{-7}$  may be achievable from the ground in the near-infrared (Beuzit et al. 2007), which would enable the detection of warm (young/massive) gas giant planets at separations  $> 0.2''$  with 10-m class telescopes. An appropriately designed 30-m telescope would enable companion detections at even smaller inner working angles. At  $4.5 \mu\text{m}$ , JWST/NIRCam coronagraphy will be capable of detecting companions at contrasts of  $10^{-6}$  at separations beyond  $1.5''$ , capturing objects like our own Jupiter in thermal emission as companions to the nearest M stars. The uncertain luminosity evolution of young giant planets clouds the picture somewhat (Marley et al. 2005), but it appears that the outer, massive planets orbiting nearby

---

<sup>1</sup>Mail Stop 183-900, JPL, 4800 Oak Grove Drive, Pasadena CA 91109, 818-354-2640, krs@exoplanet.jpl.nasa.gov

( $d < 20$  pc), young (age  $\sim < 1$  Gyr), low-mass ( $M < 0.5 M_{\odot}$ ) stars could be in view by 2015.

Imaging of protoplanetary disks will be revolutionized by ALMA, which will be able to resolve dynamical structures driven by protoplanets at angular resolutions approaching  $0.01''$ . For the more nearby debris disks, ALMA will be able to map systems brighter than 1000 zodis at  $0.1''$  resolution<sup>2</sup>; at  $20 \mu\text{m}$  JWST will resolve systems around nearby A stars with  $0.3''$  resolution; and large ground telescopes with adaptive optics will push toward the 1000 zodi sensitivity level in the near-infrared. A wealth of new data detailing the internal structure of bright circumstellar disks will be emerging in 2015, seeding a new theoretical understanding of disk structure, dynamics, and evolution.

While the advances described above will be remarkable scientific milestones, they fall well short of the goal of obtaining images and spectra of planetary systems like our own. Transits will detect inner terrestrial planets around distant stars, but spectroscopic characterization of them is highly unlikely. High contrast imaging will detect and characterize warm giant planets, but not cool objects at  $10^{-9}$  contrast like our own Jupiter and Saturn in their orbits around a solar-type star. Sharp images of dusty debris disks will be obtained, but only those with optical depths  $\sim > 1000$  times that of our own asteroid and Kuiper belts. Radial velocity surveys have singled out the nearby stars that host Jovian planets. What is currently missing from the 2015 exoplanetary science toolbox, and what we now describe, is an observatory that can study photons from these giant planets, and the terrestrial planets and exozodiacal dust clouds that may accompany them, around nearby stars like the Sun.

## 2. The Case for a Small Exoplanet Space Telescope Mission

### The Programmatic Imperative

NASA has performed significant design work on coronagraph and interferometer concepts for a Terrestrial Planet Finder mission (Levine et al. 2006; Lawson et al. 2007), and is now also considering occulter concepts. A common denominator of these design efforts is that they are driven by the need to take spectra of terrestrial planets with  $V \sim > 30$ . Large telescopes in the 4-8-m class are required to achieve this at visible wavelengths, or a constellation of 3-m telescopes in the thermal infrared. Missions like these are central to a full exploration of neighboring planetary systems; nothing would serve exoplanet science better than beginning one of them as soon as possible. However, all of these have the scope of a flagship mission. Without a major injection of new resources into space astronomy, it will not be possible to realize a full-scale TPF mission until many years after JWST has begun operations. Our community can either resign itself to waiting out JWST, or look for ways to achieve significant new exoplanet science, sooner, through more modest projects.

A major opportunity for observational progress is offered by smaller optical space telescopes. These platforms have strong design heritage, and provide the simplest approach to obtaining the high spatial that is needed. The science they would enable is the study of giant exoplanets around nearby stars in reflected light. At  $V \sim 27$ , these targets can be

---

<sup>2</sup>A  $5\sigma$  detection of the Fomalhaut debris ring can be achieved at  $450 \mu\text{m}$  in 6 hours at this resolution, according to the online ALMA sensitivity calculator

detected and characterized by low-resolution spectroscopy using a space telescope in the 2-m class, making the project small enough to proceed in parallel with JWST. Such a mission is missing from NASA’s current portfolio because of over-optimistic early assessments about the contrast achievable with groundbased adaptive optics (Angel 1994), and subsequent attempts to refit HST with an advanced coronagraph. With  $10^{-8}$  now recognized as the useful contrast limit for groundbased AO (Angel et al. 2006; Guyon 2005b; Stapelfeldt 2006) and the end of Hubble instrument opportunities, the way is clear to consider dedicated space missions targeting exo-Jupiters and the means for their implementation.

### Science Reach of a 2m-class Optical Coronagraph

- a. *Studies of Known Radial Velocity Planets.* Nine nearby stars host radial velocity planets whose apastron distances project to angular separations  $\geq 0.25''$ . These are cold objects presenting a contrast of  $\sim 10^{-9}$  in the optical and near-IR, and thus are only accessible to a space mission. Existing ephemerides allow observations to be timed to coincide with their maximum elongations. A 2-m class coronagraph could measure their colors, take spectra at  $R \sim 40$ , and provide astrometric measurements that will resolve the  $\sin i$  ambiguity in their masses. The spectra will allow  $\text{CH}_4$  and  $\text{NH}_3$  to be identified in the atmospheres, and the depth of the uppermost cloud deck to be measured. The planets’ albedo and presence of bright ring systems can be inferred using the observed photometry and planet sizes estimated from their measured masses. Multi-epoch imaging showing the planetary orbital motions will make a powerful visual impression of the reality of exoplanetary systems in the public mind.
- b. *Discovery of New Giant Planet Companions.* Radial velocity surveys are incomplete for orbital periods  $> 8$  years, for early F and hotter stars lacking strong metallic lines in their spectra, for stars with high chromospheric activity, and for planets in nearly face-on orbits. Multi-epoch imaging with a 2-m class coronagraph has the potential to discover new Jovian planets in 5-10 AU orbits around as many as 200 nearby stars. There are 30 stars within 25 pc distance that host close-in radial velocity planets, and which would be prime targets for an outer planet search. Spectral characterization of the detected objects would also be carried out.
- c. *Debris Disks and Exozodiacal Dust.* Circumstellar dust disks are maintained by ongoing collisions in belts of asteroidal and cometary parent bodies. In addition to revealing the location of these belts, debris disks act as a canvas on which unseen planets can impress dynamical signatures. A 2-m class coronagraph provides the  $0.1''$  spatial resolution needed to resolve the rings, warps, and asymmetries driven by planetary perturbations in these disks. With contrast improved  $\sim 1000$  times over HST, it also will be sensitive enough to detect disks as tenuous as our own Kuiper Belt, enabling comparative studies of dust inventory and properties across stellar ages and spectral types.
- d. *Terrestrial Planets.* For 5-10 of the brightest and nearest stars, the inner working angle of a 2-m class optical telescope may be good enough to allow detection of Earth-sized planets within the habitable zone, and to spectrally characterize them using broadband photometry. These results would provide a foretaste and motivation for a full-scale TPF mission to follow.

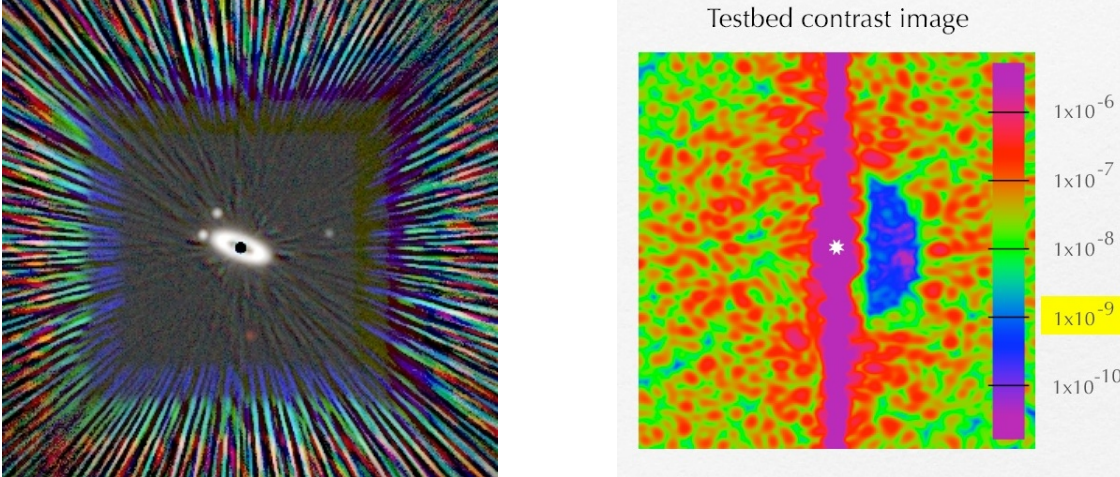


Figure 1: Left: Simulated coronagraphic image of a nearby planetary system, with Jovian planets and an inner 5 zodi dust ring as might be seen in VRI bandpasses with a 1.8-m telescope. Right: Laboratory testbed image demonstrating the state of the art in optical wavefront control (Trauger & Traub 2007)

### 3. Technical Overview

#### Wavefront Control

Precision wavefront control is the key enabling technology for ultra-high contrast imaging. It is impractical to polish a large optic to the smoothness required to directly detect exoplanets. Instead, deformable mirror(s) are used to actively correct the telescope mid-spatial frequency wavefront to the very high accuracy of  $\lambda/1000$ . In a space environment these corrections are expected to be highly stable on timescales of days, unlike the 10 ms timescales typical for groundbased adaptive optics. Over the past six years this technique has been developed in the High Contrast Imaging Testbed at NASA/JPL, to the point where contrasts of  $10^{-9}$  are now achieved at radii of 4-10  $\lambda/D$  in bandpasses of 2%, and a noise level from image to image of about 0.1 Earth or 0.01 Jupiter (Trauger & Traub 2007). This level of wavefront correction is achieved in a restricted in a “dark hole” region of the image field whose spatial frequencies can be controlled by the finite deformable mirror. Such mirrors are already available in a  $64 \times 64$  format that can support an exoJupiter mission. Work continues to refine the algorithms used to find the optimal wavefront solution, and to reduce instrumental chromatism so that broader bandpass corrections can be achieved. The key point is that the level of wavefront control needed to support  $10^{-9}$  image contrast is close to being realized. The testbed effort has been supported by the TPF project, which has requirements 10 times more stringent than an exoJupiter coronagraph mission.

#### Telescope Requirements

The use of active wavefront corrections means that the telescope primary does not need to be manufactured with extraordinary surface quality. Instead, the key telescope requirement is mechanical stability. The primary mirror must be protected from thermal stresses through the use of proper materials, temperature regulation, and shielding from outside thermal

disturbances. Primary-secondary alignment must be carefully maintained, both to keep the pupil image on the deformable mirror and to minimize focus drifts. The inner working angle (IWA) that the telescope provides to a coronagraphic instrument is determined by the alignment stability that can be achieved. For  $10^{-9}$  contrast, the usable IWA is believed to be  $3.5 \lambda/D$  for a large ( $\sim 8$ -m) telescope, but might be as small as  $2.5 \lambda/D$  for a smaller, stiffer system. While it would be highly desirable to image planets at even smaller angular separations, the telescope alignment tolerances needed to enable operation at  $< 2 \lambda/D$  are thought to be prohibitive. Continued investigation of the limiting IWA issues will be crucial for defining the sample of terrestrial planets a 2-m class telescope might reach. The size of the telescope strongly affects the number of stars that can be studied, as  $D^3$ . A monolithic, unobscured (off-axis) telescope design is preferable, as it maximizes throughput and substantially simplifies diffraction control requirements. Silver optical coatings would be used to maximize system throughput between  $0.5$ - $1.0 \mu\text{m}$ , and the reflectivity across the pupil should be uniform to within  $0.1\%$  or significant wavefront errors would be introduced. A program to develop a 1.8-m primary mirror meeting these requirements was begun by the TPF project, but then suspended due to funding cuts. The re-initiation of this Technology Demonstration Mirror (TDM) effort would be highly beneficial to the early realization of an exoJupiter coronagraph mission.

### Diffraction Control

A wealth of options are available to suppress stellar diffraction to the levels needed to image exoJupiters. A traditional Lyot coronagraph has been employed in the JPL laboratory demonstrations, focusing on graded masks that are insensitive to low-order telescope aberrations (band-limited masks). Masks made from HEBS glass have been used, but wavelength-dependent phase shifts in this material may be limiting the achievable bandwidth. Promising alternative mask materials are under investigation. A drawback of the Lyot coronagraphs is their relatively low throughputs  $< 40\%$  and loss of resolution at the Lyot stop - even for unobscured apertures. An alternative coronagraph design, dubbed Phase-Induced Amplitude Apodization (or PIAA), offers much higher throughput and spatial resolution close to that of the unobscured aperture (Guyon 2005a). It is now undergoing initial laboratory demonstration. Instead of blocking the on-axis starlight, a third option is to null it out using a copy of the input beam shifted in phase by  $180$  degrees. Subsystem laboratory testing has been done on the nulling coronagraph (Shao 2004), and it will be the focus of an upcoming sounding rocket experiment. A fourth option is the finely tailored “shaped pupil” designs that can strongly suppress diffraction along preferred directions in the image plane. Finally, an external occulter formation-flying thousands of kilometers from the telescope represents still another type of coronagraph. This is likely to be a costly exoJupiter mission option, however, because the expense of a second independent spacecraft would outweigh the savings in telescope and wavefront control requirements.

### Backend Instruments

Characterization of exoJupiters in reflected light requires an imager and spectrograph that operate over the wavelength range  $0.5$ - $0.95 \mu\text{m}$ . Existing low-noise optical CCDs would be sufficient as the detectors, and the required format would be relatively small ( $512$  or  $1024$  square). A spectral imaging instrument (Integral Field Unit) would be ideal, to enable si-

multaneous detection, spectral characterization, and speckle rejection. Other configurations such as a staring camera with filter wheel, dichroic separation into multiple simultaneous imaging channels, a long-slit spectrograph, or the long-sought energy-discriminating detectors could also be employed. The optimal instrument approach will strongly depend on the bandwidth that is achieved by the wavefront correction system. The science camera will also be used to carry out the crucial function of wavefront sensing.

#### Spacecraft and Mission Design

The spacecraft must provide a quiet and stable platform for the telescope payload while handling routine functions such as power, data handling, communications, and attitude control. Pointing would be done through a combination of coarse spacecraft body control, and fine steering of the stellar target onto the occulting spot using internal instrument mirrors. To minimize thermal disturbances to the telescope that would induce alignment instability, an Earth-trailing or L2 orbit is preferred. Studies to date suggest that a 2-m class payload can be injected into these orbits using a Delta II class launcher. If sent to L2, the spacecraft would require an on-board propulsion system for orbit maintenance. A mission lifetime of 3-5 years is required to search for outer planets with 12-20 year orbital periods; this gives the planets enough time to move from inferior conjunction to maximum elongation, where they will be bright and well-separated from their parent star.

### 4. A New Programmatic Approach

A 2-m class coronagraphic space telescope is an important first step toward the goal of directly imaging and spectrally characterizing planetary systems around nearby stars like the Sun. It would produce important science, set the stage for subsequent TPF missions, and is close to technical readiness. Unfortunately, NASA lacks a programmatic avenue that would allow this class of mission to go forward. The NASA Navigator Program currently encompasses only groundbased efforts, SIM, and the large TPF missions; no provision has been made for “probe” missions of intermediate scale. The community has tried to overcome this omission, with several groups repeatedly proposing 1.2-1.8-m coronagraphic telescopes to the NASA Discovery Program. These have consistently been declined, primarily on the basis of cost. **The situation is at an impasse: unless something is done, direct imaging of planetary systems like our own will be left waiting more than a decade for the coveted flagship missions, and unable to pursue important, more affordable missions that could be realized on a 5 year timescale.** The NASA New Frontiers Program represents the mission class (\$650 M) that could support the scope of a 1.5-2-m coronagraphic telescope. A specific exoplanet probe mission opportunity like this is urgently needed under the auspices of the Navigator Program. In such a vehicle, a 2-m class coronagraph could be weighed against other exoplanet probe mission concepts, with an open competition for the best instrumental approaches. It is urgent that the Exoplanet Task Force consider this or other options that would enable near-term progress in the direct detection of nearby planetary systems like our own.

## References

- Angel, R.J.P. 1994, *Nature* 386 203
- Angel, R.J.P, Codona, J., Hinz, P., Close, L. 2006, *SPIE* 6267 73
- Beuzit, J.-L., Mouillet, D., Oppenheimer, B.R., Monnier, J.D. 2007 in *Protostars and Planets V*, Univ. of Arizona Press, pp. 717-732
- Charbonneau, D., Brown, T., Burrows, A., Laughlin, G. 2007 in *Protostars and Planets V*, Univ. of Arizona Press, pp. 701-716
- Guyon, O. 2005a *Ap.J.* 622 744
- Guyon, O. 2005b *Ap.J.* 629 592
- Lawson, P.R., Lay, O.P, Johnston, K.J., Beichman, C.A. Eds. 2007, TPF-I SWG Report, JPL Publication 07-1
- Levine, M., Shaklan, S., Kasting, J. eds. 2006, TPF-C STDT Report, JPL document D-34923
- Marley, M., Fortney, J., and Hubickyi, O. 2005 *DPS* 37 25.05
- Rivera, E.J. et al. 2005 *Ap.J.* 634 625
- Shao, M. et al. 2004 *SPIE* 5487 1296
- Stapelfeldt, K.R. 2006 in *The Scientific Requirements for Extremely Large Telescopes*, IAU 232 Proceedings, Cambridge Univ. Press, pp. 149-158.
- Trauger, J.T. and Traub, W.A. 2007 *Nature* April 12.
- Udry, S., Fischer, D., and Queloz, D. 2007 in *Protostars and Planets V*, Univ. of Arizona Press, pp. 685-700